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THERMAL AND SOLUTAL BUOYANCY EFFECTS ON MIXING OF OPPOSED LAMINAR JETS IN A TWO-DIMENSIONAL PASSIVE MIXER AT A HIGHER REYNOLDS NUMBER

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ABSTRACT

Numerical analysis of two opposing streams of different fluids having different temperatures (same phase, miscible) in a 2-D adiabatic channel, is numerically investigated in the mixed convection laminar flow regime. The thermal and solutal buoyancy effects in aiding configuration (upper jet heavy and lower jet hot) have been considered through the Boussinesq approximation. Hasan & Khan [7] investigated in detail the effect of variation of Richardson numbers on flow dynamics & mixing of streams at Re = 200. It is decided to carry out numerical experiments at higher Re (Re = 400) and with three combinations of thermal Richardson number (Ri_T) & solutal Richardson number (Ri_C) namely, (0.5, 1), (1, 0.5) & (1, 1). Within the parametric space of the present study, unsteady, oscillatory periodic flow with vortex shedding is obtained for all conditions. The combined value of Richardson numbers (Ri_T + Ri_C) effect the flow and mixing rather their individual values. With higher combined value of Richardson number better mixing is achieved in shorter mixing lengths.

***KEYWORDS:** Double Diffusive, Mixed Convection, Higher Reynolds Number, Laminar & Mixing*

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Original Article

INTRODUCTION

Jet-jet impingement is a phenomenon that comes under a wider umbrella of interactions, categorized under jet impingement. Study of jets-wall and jet-jet impingement configuration have been so inclusive in the field of fluid mechanics as it is in our lives, in the form of some notable industrial and domestic applications like in impinging jets atomizers, chemical reactors, heat exchange in the material processing, cooling of leading edge of the gas turbine blade, manufacturing of tempered glasses and many more. Krupa et al. [1] experimentally studied the characterization of T-jet micromixers with different geometries under the effect of Reynolds number (Re) and jet flow rate ratio. The micromixer consists of 1-Naphthol and diazotized Sulfanilic Acid, both being in aqueous media. They found that the mixing was enhanced at low Reynolds number with the jet flow ratio tending towards unity. In another numerical investigation by Mashaei et al. [2], the effect of Reynolds number on one-way opposed non-Newtonian jets was examined and it was concluded that with the increase of Re the thermal mixing improved. However, decrease in Re along the channel resulted in an increased thermal mixing too. Likewise, the effect of Re in the mixing of water and glycerol–water solution was investigated by Shi et al. [3] in a confined impinging jet reactor (CIJR) using PLIF (planar laser induced fluorescence). This study was carried out with and without

excitation at 100≤Re≤500. It was observed that the mixing was poor at Re≤100 while it improved significantly along with the evolution of oscillatory regime at Re≥150. In another experimental study, Li et al. [4] studied the mixing characteristics in T-jet reactors with three different geometries with the inflow pulse excitation ranged 0.5-25 Hz. It was observed that in T-jet mixers while the flow was in transition from being segregated to the oscillatory regime, Reynolds number primarily improved the mixing. Also, at lower Reynolds numbers, the mixing can be improved by exciting the pulsed inflow with low frequencies as a result of periodic oscillation. Recently, an experimental study was carried out by Dundi et al. [5] to characterize the mixing in a T-T mixer with cylindrical elements. the experiments were performed to evaluate the quality of mixing at Re ranging from 6 to 700. It was found that T-T mixer with cylindrical elements gave a very good mixing as compared to the simplistic T-mixer at the given range of Reynolds number. Khan et al. [6] performed a two-dimensional numerical study to investigate the effects of Reynolds number (100, 200 & 300) on the passive mixing of double diffusive opposed jets. The values of Thermal and concentration-based Richardson number are taken as unity with Prandtl number and Schmidt number as 0.7 & 0.8 respectively. A steady flow and better thermal mixing were observed at Re=100. However, the flow becomes unsteady and experiences vortex-shedding at Re=200 & 300. Thermal mixing was improved at Re=100 whereas Re=300 shows better physical mixing. Physical and thermal mixing reach their minimums at Re=200.

In the present work involves the numerical simulation of interaction of two non-isothermal opposing jets of different fluids (in this case, single phase & miscible) in a two-dimensional passive mixer/channel in a mixed convection laminar flow regime and to further inspect the effects of the thermal and intrinsic buoyancy forces (which have been considered through Boussinesq approximation) at a higher Reynolds number (Re = 400). In addition to the Prandtl (Pr = 0.7), Schmidt (Sc = 0.8) and the Reynolds numbers, the buoyancy forces (thermal and intrinsic) give rise to temperature-based Richardson number (Ri_T) and concentration-based Richardson number (Ri_C) respectively as the dimensionless numbers in the governing equations. So, the effects of Ri_T and Ri_C (combination of 0.5& 1.0) has to be investigated on flow structure and mixing characteristics of opposed interacting streams in a 2D rectangular channel.

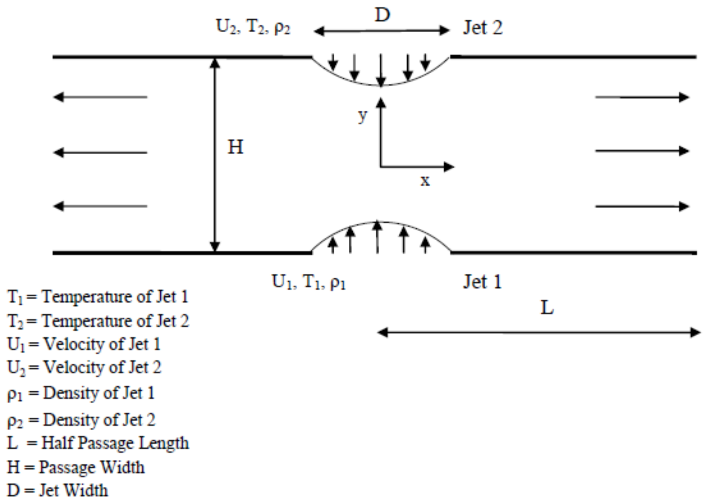


Figure 1: 2-D Configuration of Passive Mixture Parameters is Presented in the Present Work

METHODOLOGY

In the present study, the fluid in the flow region (as shown in Figure 1) is taken as a binary non reacting mixture. Therefore, properties or the operating variables like velocity of the jets, pressure, density, temperature and mixture

concentration can be taken to describe the local flow conditions.

The governing equations of overall mass conservation, transportation of momentum, energy and the concentration of mixture are used to model the physical flow subject to Boussinesq approximation are:

Overall Mass Conservation: $\nabla \cdot \vec{V} = 0$

Momentum: $\dfrac{D\vec{V}}{D\tau} = -\nabla p + \left\{-Ri_T\theta + Ri_C\overline{C}\right\}\vec{\varepsilon}_g + \dfrac{1}{Re}\nabla^2\vec{V}$

Energy Transport: $\dfrac{D\theta}{D\tau} = \dfrac{1}{Re \cdot Pr}\nabla^2\theta$

Mass Transport: $\dfrac{D\overline{C}}{D\tau} = \dfrac{1}{Re \cdot Sc}\nabla^2\overline{C}$

The profiles for inlet jet velocity are to be considered as parabolic in nature. Since there are two inlet jet streams; one is hot and other one is cold and their uniform temperatures (dimensionless) are taken as fixed at +0.5 and -0.5 respectively. The concentration of jet with greater mass is taken as +0.5 and that of jet with lighter mass is taken as -0.5. For the velocity components at the solid channel walls, non-penetrative and no-slip condition is used.

The walls of the rectangular channel are adiabatic and the rate of flow of mass per unit area is taken as zero. For more details, refer to Hasan and Khan [7].

Numerical Scheme

Semi-implicit and a pressure-correction schemes [8,9] are used to carry out the computer simulations on a non-staggered mesh. A non-staggered mesh can cause grid-scale pressure oscillations to arise. So as to avoid that, “momentum interpolation” concept has been used [10,11].

Using a two-step Predictor–Corrector approach, at a given instant of time, the flow field is moved forward in time. In predictor step, using explicit two-point Adam-Bashforth integration, the governing equations for transportation of mass, momentum and energy are marched forward in time. It resulted in second order accurate estimates of provisional velocities, temperature and concentration of the binary fluid mixture. In corrector step, for continuity through a pressure correction field, the provisional estimates of velocity are corrected. As described by Hasan and Khan [7], The pressure correction field is obtained via pressure correction Poisson equation.

Validation

The code used in the present study has been validated. Details of validation were given in Hasan and Khan [7].

RESULTS AND DISCUSSIONS

Hasan & Khan[7] carried out detailed investigation of effect of Ri_T & Ri_C on flow characteristics and mixing phenomena of opposed impinging streams at Re = 200 as reported earlier. In the present study, it is considered to observe these effects at higher Reynolds number (Re = 400). The numerical data is examinedfor the effect of higher Reynolds number on the flow characteristics using plots of mean streamlines, isotherms and iso-concentration and time history of

flow variables sampled at specific locations. For unsteady cases mean plots are prepared from average data over time period of minimum frequency wave. These plots are prepared after the flow has settled into a long-term stable state (steady or unsteady). The mixing of the two jets is examined using scalar measures such as Mixing Index (MI) and Length (L_m) are used (Ref. [7]).

The geometry is fixed with h = 2 and ℓ = 100. A 379 × 129 mesh is used in computations. The mesh is depicted in figure 2.

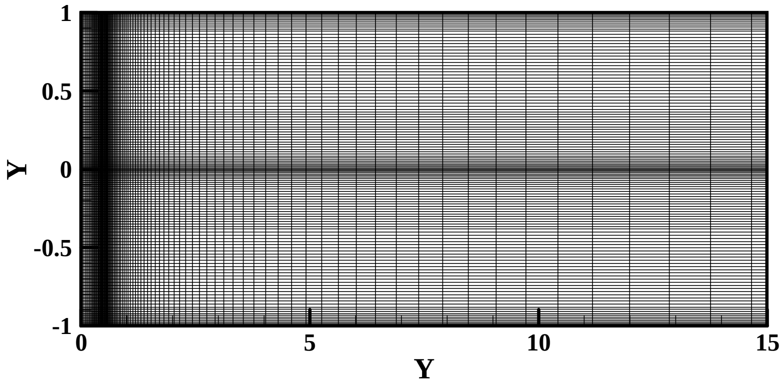


Figure 2: A 379 × 129 Mesh Used in Present Computations [7]

All the simulations are carried out at three combinations of (Ri_T, Ri_C) namely (1.0, 1.0), (1.0, 0.5) & ().5, 1.0); Re = 400, Pr = 0.7, Sc = 0.8 and equal jet velocities. The value of Re is based on average velocities of the two jets. The average properties of the two jets are employed in the definitions of the various dimensionless numbers. The flow is symmetric about the axis of the jets, so all plots presented are for half domain only. In all these cases, in the limit of large times, the flow evolves into an oscillatory periodic state. The oscillatory behaviour of flow with periodicity apparent in fig.ure 3 which show the time history of u-velocity at (-15.56, 0) for the three combinations of Ri_T & Ri_C. Comparing the time histories in fig.ure 3, it can be readily observed that qualitatively they are all same with frequencies and amplitudes of combination of (Ri_T, Ri_C) of (0.5, 1.0) & (1.0, 0.5) are more near to each other but both distinct from (1.0, 1.0).

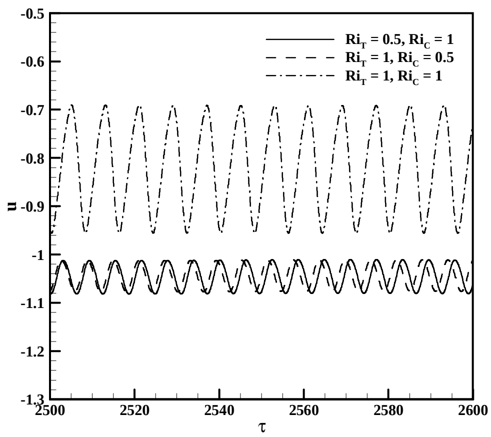


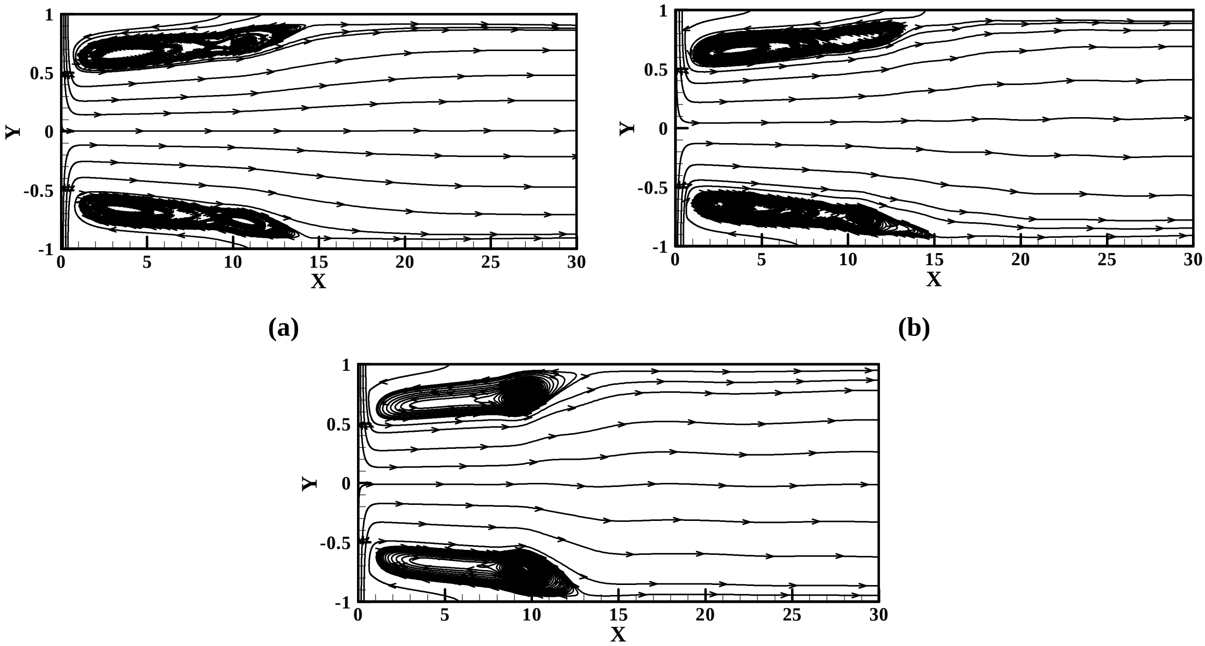
Figure 3: Time History of u (-15.56, 0) at Sc = 0.8, 1.0 and 1.2

Presented in Table 1 are the shedding frequencies obtained when flow developed in stable oscillatory flow. The frequency for highest combined Richardson number i.e. 2 (Ri_T = 1 + Ri_C = 1) is lowest, followed by (Ri_T, Ri_C) combination of (1.0, 0.5) and combination of (0.5, 1.0) has maximum frequency. Although the difference between frequencies of combination of (Ri_T, Ri_C) 0f (1.0, 0.5) & (0.5, 1.0) is 0.007 which is quite small. This suggests the exchanging values of two Richardson numbers has no significant effect on flow velocities.

Table 1:Variation of Shedding Frequency with Richardson No. at Reynolds N0. = 400

Ri_T	Ri_C	Shedding Frequency
1	1	0.0083
1	0.5	0.0095
0.5	1	0.0102

Plots of mean streamline three combination of (Ri_T, Ri_C) viz. (0.5, 1.0), (1.0, 0.5) & (1.0, 1.0) are shown in figure 4(a)-(c) respectively. It is evident from the stream traces of the three cases considered that they are qualitatively same. The mean plot shows that stream traces appear to be steady in the flow between the separation zones and further downstream. Again, the qualitative nature of streamline plots for (Ri_T, Ri_C) of (0.5, 1.0) & (1.0, 0.5) are same and differs from that for (1.0, 1.0).



(a) (b)

(c)

Figure 4: Mean Stream Patterns at a) Ri_T = 0.5, Ri_C = 1.0; b) Ri_T = 1.0, Ri_C = 0.5; and c) Ri_T = 1.0, Ri_C = 1.0

Presented in figures 5 (a)-(c) are mean isotherm & in figure 6 (a)-(c) iso-concentration plots for three combination of (Ri_T, Ri_C) namely, (0.5, 1.0), (1.0, 0.5) & (1.0, 1.0) respectively. The high intensity of lines in impingement zone indicates intense physical and thermal mixing in that region. It is quite evident from figure 5 & figure 6 that qualitatively both isotherm and iso-concentration patterns are same. Also, for combination of (Ri_T, Ri_C): (1.0, 1.0) it is apparent thatflow is nearly mixed in half the length as for other two cases considered in present simulations. Further higher gradients for

combination of (Ri_T, Ri_C), equal to (1.0, 1.0), shows higher mixing rate as compared to that of other two combinations of Ri_T&Ri_C.

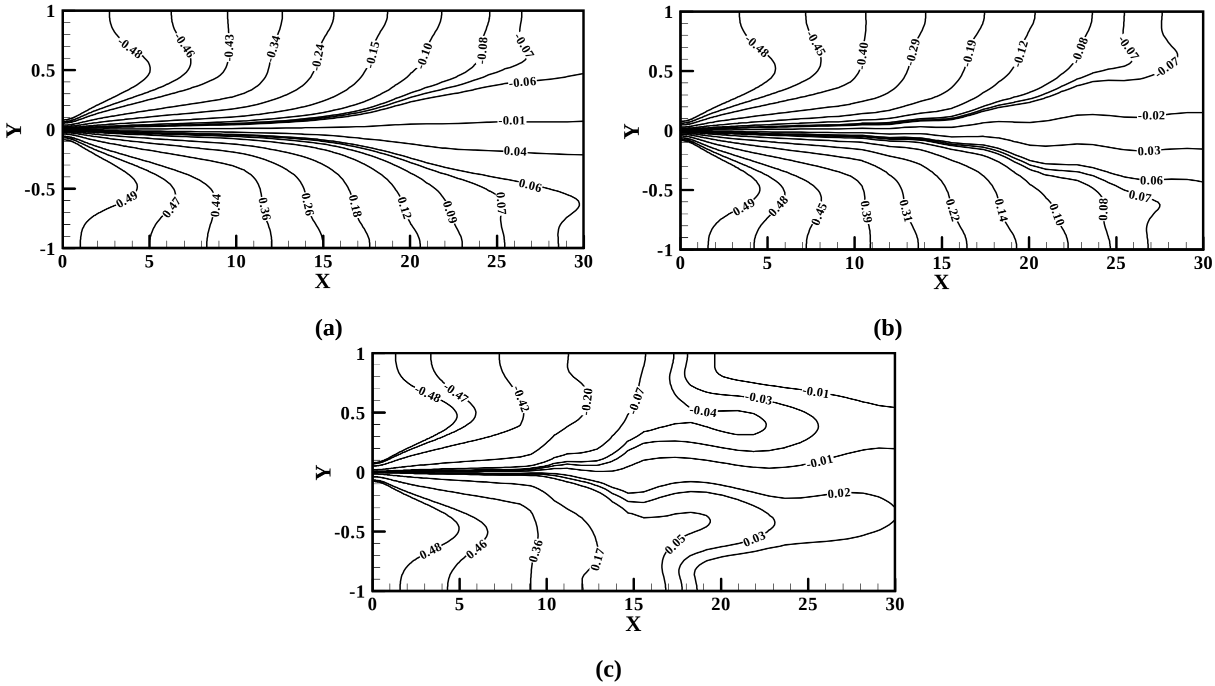


Figure 5: Plots of Mean Iso-Thermal patterns at Re=400 for: (a) Ri_T=0.5, Ri_C=1.0 (b) Ri_T=1.0, Ri_C=0.5 and (c) Ri_T=1.0, Ri_C=1.0

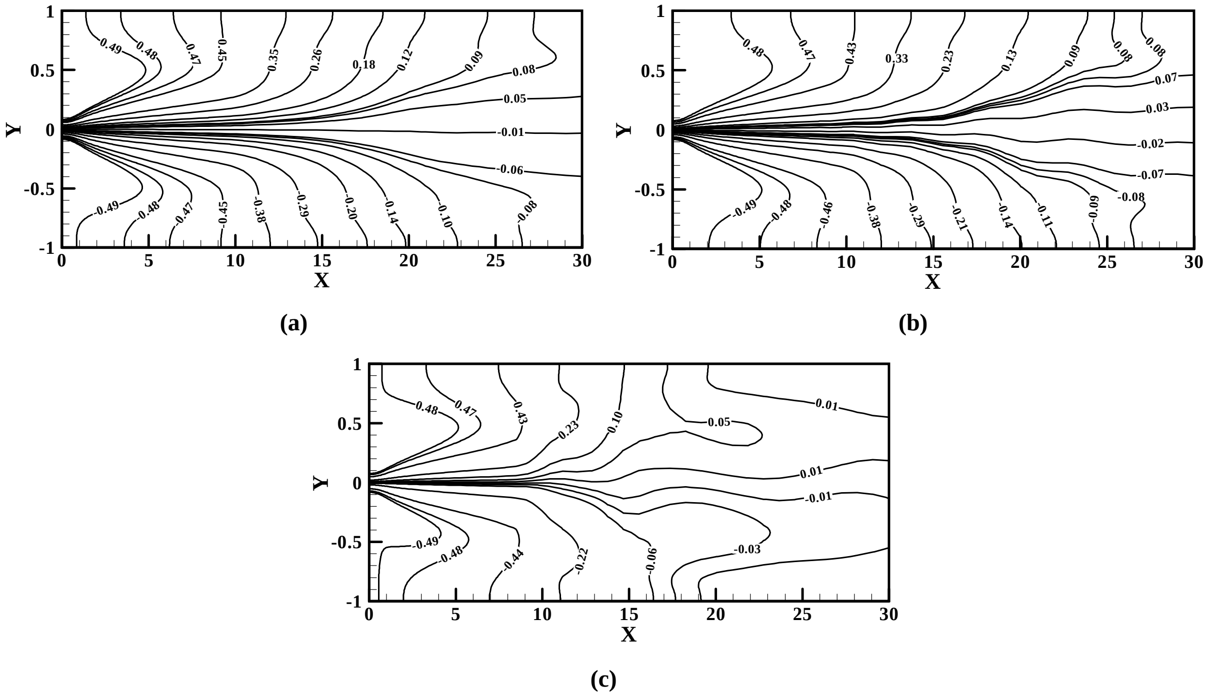


Figure 6: Plots of Mean Iso-Concentration Patterns: (a) Ri_T=0.5, Ri_C=1.0 (b) Ri_T=1.0, Ri_C=0.5 and (c) Ri_T=1.0, Ri_C=1.0

Present study is important from point of view of both thermal and physical mixing of the two impinging streams. Achieving better mixing in shorter channel lengths is important from *Mixer Design* point of view. Mixing phenomena is quantified by two scalar measures viz.*bulk based Normalized Mixing Index* (MI_T& MI_C) and *Mixing Length* (L_{mT}&L_{mC}) [7]. Bulk based mixing index gives an indication of the instantaneous deviation of the state of fluid at any axial section from the thermodynamically attainable bulk values (of temperature and concentration), whereas mixing length give a measure of the length from the centre of the channel to a point where *90%* mixing is achieved.

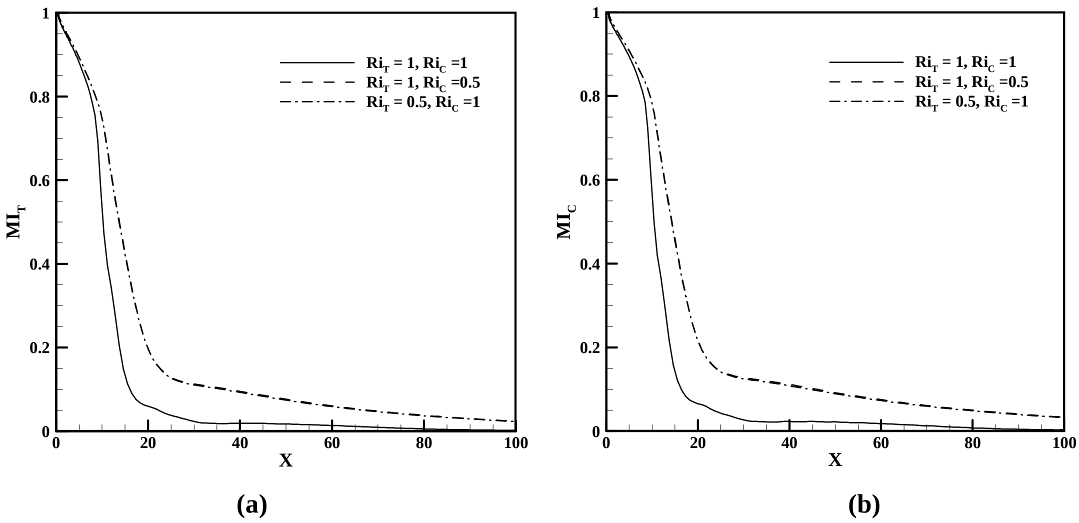


Figure 7: Bulk Based Normalized Mixing Index Plots for (a) Temperature & (b) Concentration

Figure 7 illustrates the plots of bulk based normalized mixing index for (a) Temperature & (b) Concentration respectively. The lines for (Ri_T.Ri_C) equal to (0.5, 1.0) & (1.0, 0.5) overlap each other for both MI_T & MI_C. It is clear from figure 7 that for values of Ri_T = 1.0 & Ri_C = 1.0, both thermal &solutal mixing is higher as compared to other two combination of Richardson numbers considered in the present study.

Table 2: Temperature and Concentration Mixing Lengths Various Combinations of Richardson No. at Re = 400

Case	(Ri_T, Ri_C)	L_{mT}	L_{mC}	Complete Mixing Max [L_{mC},L_{mT}]
I	(0.5, 1.0)	36.053	44.336	44.336
II	(1.0, 0.5)	37.537	45.774	45.774
III	(1.0, 1.0)	16.087	16.380	16.380

Table 2 presents the thermal & concentration based mixing lengths for the combination of Ri_T & Ri_C considered in the present study. **L_{mT}** for *cases I & II* differ by less than **4 %** where as L_{mT} for *case III* is less than L_{mT} for *case II* by approx. **57 %** which indicates that lesser channel lengths required in *case III* as compared to *case I* & *case II*. Also L_{mC} & L_{mT} are comparable for *case III* but differ by around 8 units for *case I &II* which is probably due to fact that different rates of thermal & concentration diffusion (due to different values of *Pr* & *Sc* numbers) become less prominent at higher *Richardson number*.

CONCLUSIONS

- For the given combinations of Ri_T&Ri_C flow is long time unsteady having periodic oscillatory behaviour with vortex-shedding.
- Switching the two Richardson number neither effects flow dynamics nor mixing much.
- With higher combined value of Richardson number ($Ri_T + Ri_C$) better mixing is achieved in shorter mixing lengths.
- Complete mixing length with value **45.774**, is maximum for *case II* and minimum with value **16.380**, for *case III*.

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